EVOLUTION OF MAGNETIC FIELDS AND MASS FLOW IN A DECAYING ACTIVE REGION

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Abstract. Five days of coordinated observation were carried out from 24–29 September, 1987 at Big Bear and Huairou Solar Observatories. Longitudinal magnetic fields of an αp sunspot active region were observed almost continuously by the two observatories. In addition, vector magnetic fields, photospheric and chromospheric Doppler velocity fields of the active region were also observed at Huairou Solar Observatory. We studied the evolution of magnetic fields and mass motions of the active region and obtained the following results: (1) There are two kinds of Moving Magnetic Features (MMFs). (a) MMFs with the same magnetic polarity as the center sunspot. These MMFs carry net flux from the spot, move through the moat, and accumulate at the moat's outer boundary. (b) MMFs in pairs of mixed polarity. These MMFs are not responsible for the decay of the spot since they do not carry away the net flux. MMFs in category (b) move faster than those of (a). (2) The speed of the mixed polarity MMFs is larger than the outflow measured by photospheric Dopplergrams. The uni-polar MMFs are moving at about the same speed as the Doppler outflow. (3) The chromospheric velocity is in approximately the opposite direction from the photospheric velocity. The photospheric Doppler flow is outward; chromospheric flow is inward. We also found evidence that downward flow appears in the photospheric umbra; in the chromosphere there is an upflow.

1. Introduction

Moving magnetic features (MMFs) were discovered by Sheeley (1969). They are numerous small magnetic features in a mix of both polarities flowing away from the center sunspots (Harvey and Harvey, 1972, 1973; Vrabec, 1974). Due to MMFs, decaying spots often have an annular 'moat' around them through which the flux elements move. The moat is essentially free of long-lasting magnetic structure. Doppler velocity in the moat has been observed by Sheeley (1972). It was found that velocities measured by tracking the magnetic elements and the Dopplergrams are about the same (Wang, 1988). Maltby (1975) used the photographic subtraction technique and found that the flow is concentrated in channels. Dialetis, Mein, and Alissandrakis (1985) pointed out that there is a maximum velocity inside the penumbra in the photosphere and well outside the penumbra in the chromosphere. Gilman (1986) assumed that the outflow is carrying flux away from the sunspot. The way that the magnetic fluxes transfer from sunspots to their surroundings still requires observational proof. Most of the previous studies on MMFs and their relationship to the Evershed flow were based on observations of longitudinal magnetic fields over a few hours. In this paper, we will discuss the long-term evolution of a decaying active region and magnetic field transfer

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from the sunspot, based on a 75-hour coordinated observation between Big Bear Solar Observatory (BBSO) and Huairou Solar Observatory. We will also study the relationship between the chromospheric and photospheric velocity fields and the vector magnetic field of the sunspot. During the period of 24–29 September, 1987, the longitudinal magnetic fields of a decaying active region (AR 4855) are observed almost continuously at Big Bear and Huairou Solar Observatories. The target consists of an αp sunspot and surrounding enhanced network. We achieved 75-hour coverage with four night gaps of six to eight hours. The images were then combined, producing a continuous movie. Wang *et al.* (1989) have demonstrated our preliminary results based on this set of data. The authors found that the principal loss of magnetic flux appears to be due to 'cancellation' at the main neutral line. The extent of the moat was reduced by 50% in 75 hours. The flares occurred a few hours before the flux disappearance took place. The e-folding lifetime of the magnetic network is 80 hours and that of individual magnetic elements is 92 hours.

2. Observation and Data Reduction

The BBSO Videomagnetograph (VMG) System was originally developed by Leighton and Smithson (Mosher, 1977) and has been improved in recent years (Zirin, 1985). This system has made it possible to study very weak photospheric magnetic structures. The vector videomagnetograph system at Huairou Solar Observing Station, located on an island in the Huairou reservoir 60 km NE of Beijing, was designed by Ai (1987). It consists of a 35-cm vacuum telescope, a $\frac{1}{8}$ Å birefringent filter with 3 sets of KD*P crystal modulators, a CCD camera and an Imaging Technology 151 system controlled by an AST-386 system, which transmits the data to a Vax/11–750. It works at either of the two spectral lines: Fe I λ5324.19 Å (Ai, Li, and Zhang, 1982; Zhang, 1986) for photospheric magnetic and line-of-sight velocity observations and H$\beta\lambda$4861.34 Å (Zhang and Ai, 1986) for chromospheric observations. The field of view is about $5.7' \times 4'$. The pixel resolution is about $0.7'' \times 0.4''$. In fine seeing conditions, the smallest observable magnetic features are less than $2''$ across. The longitudinal component (Stokes parameter V) of the vector magnetic field in the solar photosphere was measured at 0.075 Å from the line center of Fe I λ5324.19 Å and the transverse components (Stokes parameters Q and U) at the line center. The photospheric Dopplergrams were measured with the subtraction technique at ± 0.15 Å from the line center of Fe I λ5324.19 Å, the chromospheric Dopplergrams at ± 0.24 Å from the center of Hβ λ4861.34 Å. After doing a 3×4 pixel ($2'' \times 2.1''$) spatial average and integrating 255 frames, the signal to noise ratio is

$$s/n = 70 \times \sqrt{4 \times 3} \times \sqrt{2 \times 255} = 5600\,,$$

corresponding to ± 2 G for the photospheric longitudinal field, ± 15 G for the photospheric transverse field, $\pm 2\ \mathrm{m\ s^{-1}}$ for the photospheric line-of-sight velocity field and $\pm 8\ \mathrm{m\ s^{-1}}$ for the chromospheric velocity field. Each Dopplergram integrates 4096 frames and takes about 330 s, so the 5-min oscillation can be reduced significantly. We also made spatial averages to smooth the small-scale velocity fields.

3. The Evolution of Magnetic Fields of the Sunspot

3.1. The vector magnetic structures of the sunspot

The decaying active region is located 14° N, at CMP on 22 September, 1987. Figure 1(a) shows a white light image, and Figure 1(b), a vector magnetogram of the region on 25 September. The longitudinal fields are plotted as the contours; the transverse fields are plotted by bars. The α sunspot has negative magnetic polarity, the leading plarity of the northern hemisphere. Note that positive flux occurred in the right (west side of the spot. This apparent polarity reversal is due to the projection effect when the target is away from the solar disk center (Wang *et al.*, 1989). The positive structure intrudes gradually into the penumbra of the spot from 25–27 September as the region rotates closer to the west limb. The transverse field is much stronger when the region is closer to the limb. Again, this is due to the projection effect. Outside the penumbra, the sunspot is surrounded by a moat of roughly twice the penumbral radius. Network magnetic elements in Figure 1 around the spot mark the outer edge of the moat.

3.2. The outward flow of sunspot magnetic flux

Figure 2 shows the general velocity pattern of this active region, which is measured by tracking the motion of magnetic elements. In the westward side of the sunspot, the MMFs are almost exclusively monopolar and of opposite polarity to the umbral field. This is due to the projection effect of the tilted magnetic lines of force, when the region is off the disk center. By following individual MMFs carefully, we found that there are two kinds of MMFs. (1) MMFs in pairs of mixed polarity, which we call 'mixed polarity MMFs'; (2) MMFs with the same polarity as the central sunspot, which we call uni-polar MMFs. When the MMFs move to the boundary of the moat, one of followng two events might occur: (1) If there are two elements of opposite polarities, the fluxes are cancelled (e.g., elements A and B in Figure 3); (2) If the element has the same polarity as the center spot, it merges and enhances the boundary of the moat (element C in Figure 4). We measured the flux changes of the sunspot. The flux of negative polarity decreased at a rate of 10^{20} Mx h^{-1} on 25 September and 4×10^{19} Mx h^{-1} on 26 September; the positive flux increased at a rate of 10^{18} Mx h^{-1} on 25 September and decreased at 0.8×10^{17} Mx h^{-1} on 26 September. The increase of the positive flux was caused by the apparent reversal of the magnetic polarity due to the projection effect. Note that the decrease of the negative flux is not significant; it may be due to error of observation.

4. Doppler Measurements in the Vicinity of the Sunspot

Doppler measurements in the vicinity of sunspots (Sheeley and Bhatnagar, 1971; Sheeley, 1972) provided evidence for the horizontal outflow extending roughly 10000 to 20000 km beyond the penumbral boundary. It was suggested by Leighton (1963) that the sunspot might be a super-large and super-powerful supergranulation cell and by

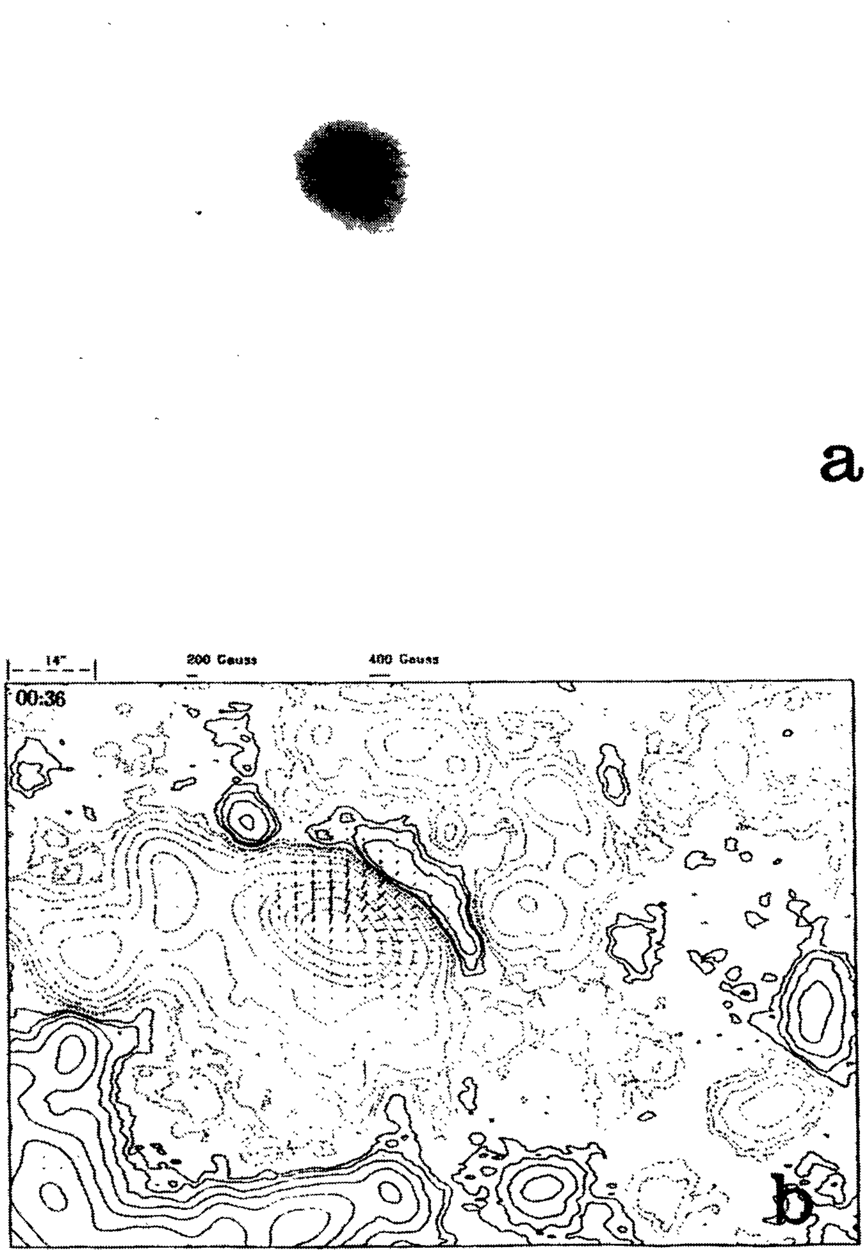

Fig. 1. The decaying active region observed on 25 September, 1987. (a) Gray scale maps of photospheric monochromatic picture of an αp sunspot (Fe I λ5324.19 Å). (b) Photospheric vector magnetogram. Solid (dashed) contours correspond to positive (negative) fields. Contour levels are 5, 20, 40, 80, 160, 320, 640, 960 G. North is at the top, west is at the right.

Sheeley (1972) that a decaying sunspot occupies the center of a supergranule and small-scale fragments of magnetic flux are carried away from sunspots by the supergranular flow. The average outflow velocity from Doppler measurements is about 0.5–1.0 km s^{-1} in the photosphere. Simultaneous measurements of the velocity field

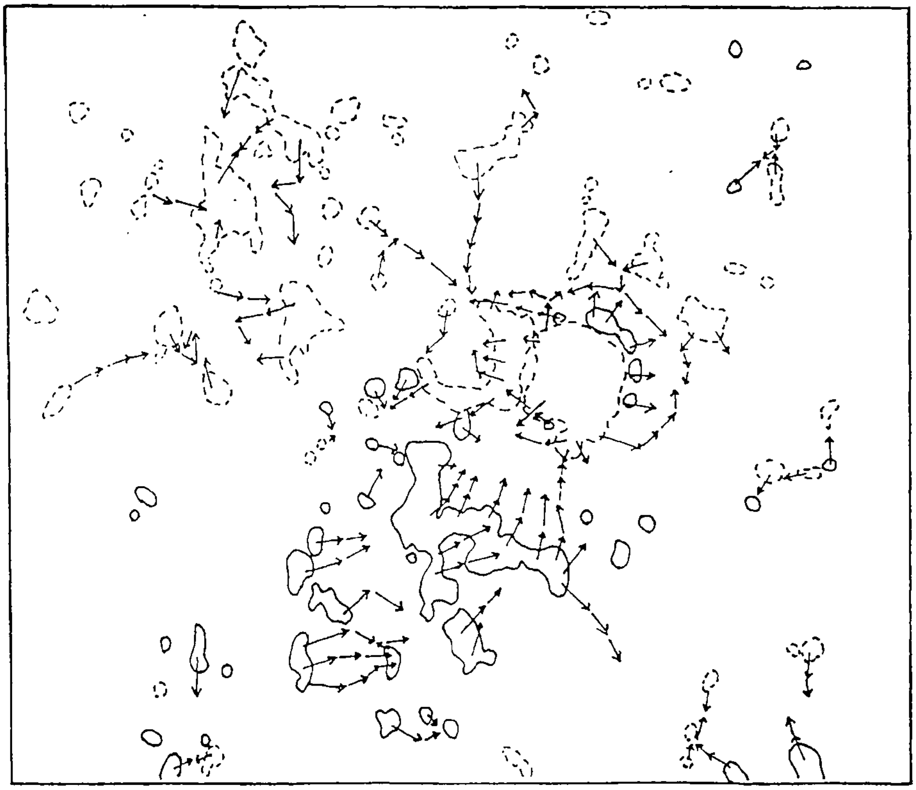

Fig. 2. The large-scale velocity pattern of the magnetic features in the decaying active region, averaging over 25–27 September, 1987. The arrows show the direction of motion and distance moved in 43 hours.

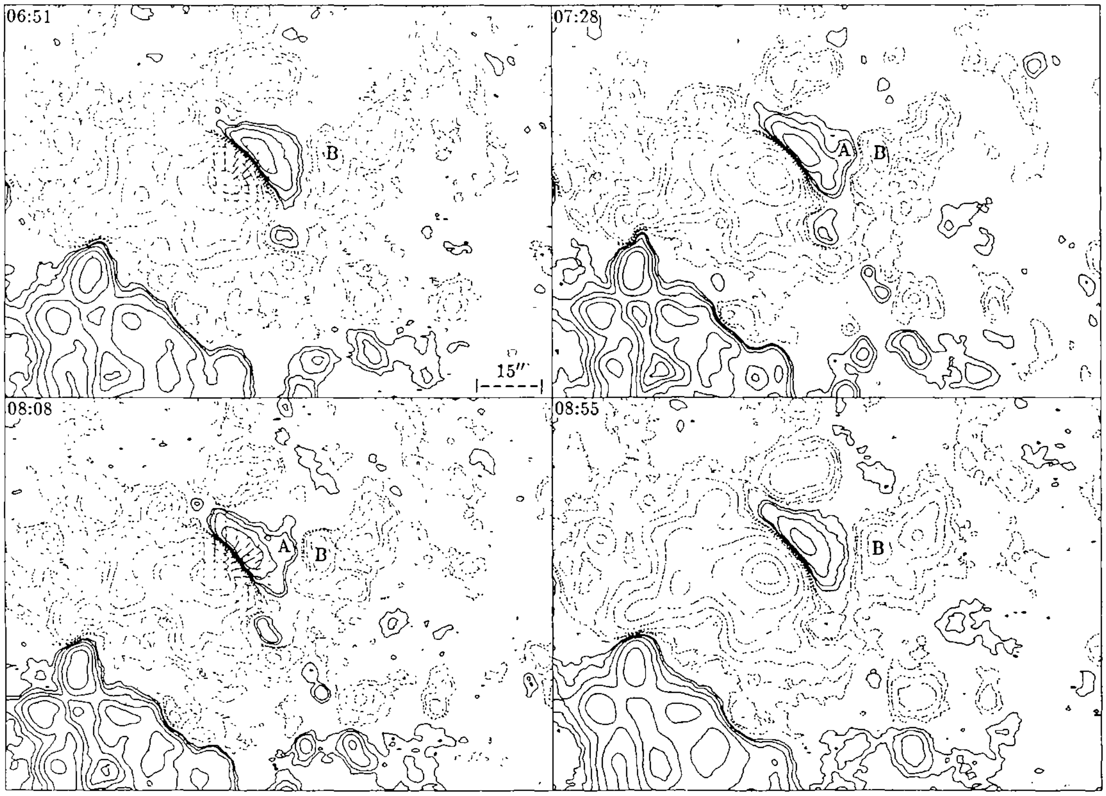

Fig. 3. A sequence of vector magnetograms of 26 September, 1987. The MMF element 'A' moves to the boundary of the moat and is cancelled with the element 'B'.

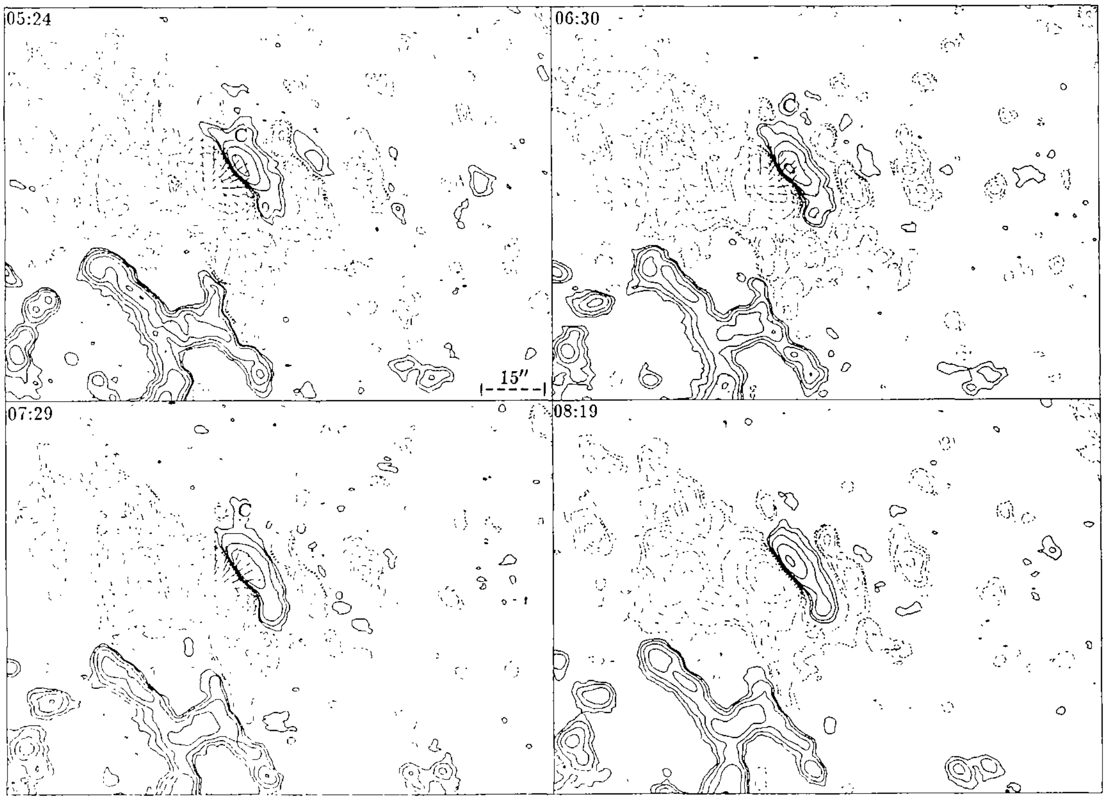

Fig. 4. A sequence of magnetograms of 27 September, 1987. C marks an uni-polar MMF.

and the magnetic field make it possible for us to compare the velocity of MMFs and the sunspot Doppler outflow. Also, we have two-level Doppler measurements: Hβ for chromosphere, 5324 Å for photosphere. In Figure 5, we show chromospheric and photospheric Dopplergrams corresponding to the vector magnetograms in Figures 3 and 4. Two line-of-sight magnetograms are included for comparison. The upflow motion appears as dark features; downflow, bright features. When the target is far away from the disk center, the line-of-sight velocity generally represents the horizontal velocity.

4.1. The photospheric mass flows of the sunspot

The profiles of velocity and magnetic fields through the sunspot are shown in Figure 6. Figure 6(a) shows the longitudinal and transverse magnetic field strength, and line-of-sight chromospheric and photospheric velocity of 26 September; Figure 6(b) shows those of 27 September. Note that the red shift (white features in Figure 5) appears on the photospheric umbra as negative velocity plotted in Figure 6. Grigoryev and Pevtsov (1987) demonstrated that in the umbra the directions of magnetic field and velocity field coincide. So the flows in the umbra travel radially away or into the solar surface. Therefore, the observed red shift is the true radial inflow into the umbra. However, in the penumbra and outside the penumbra, the flows are more transverse, so the observed line-of-sight velocity is actually the projected transverse Doppler flow. Like most other spots, the Doppler flow is much more obvious when the region is closer to the limb,

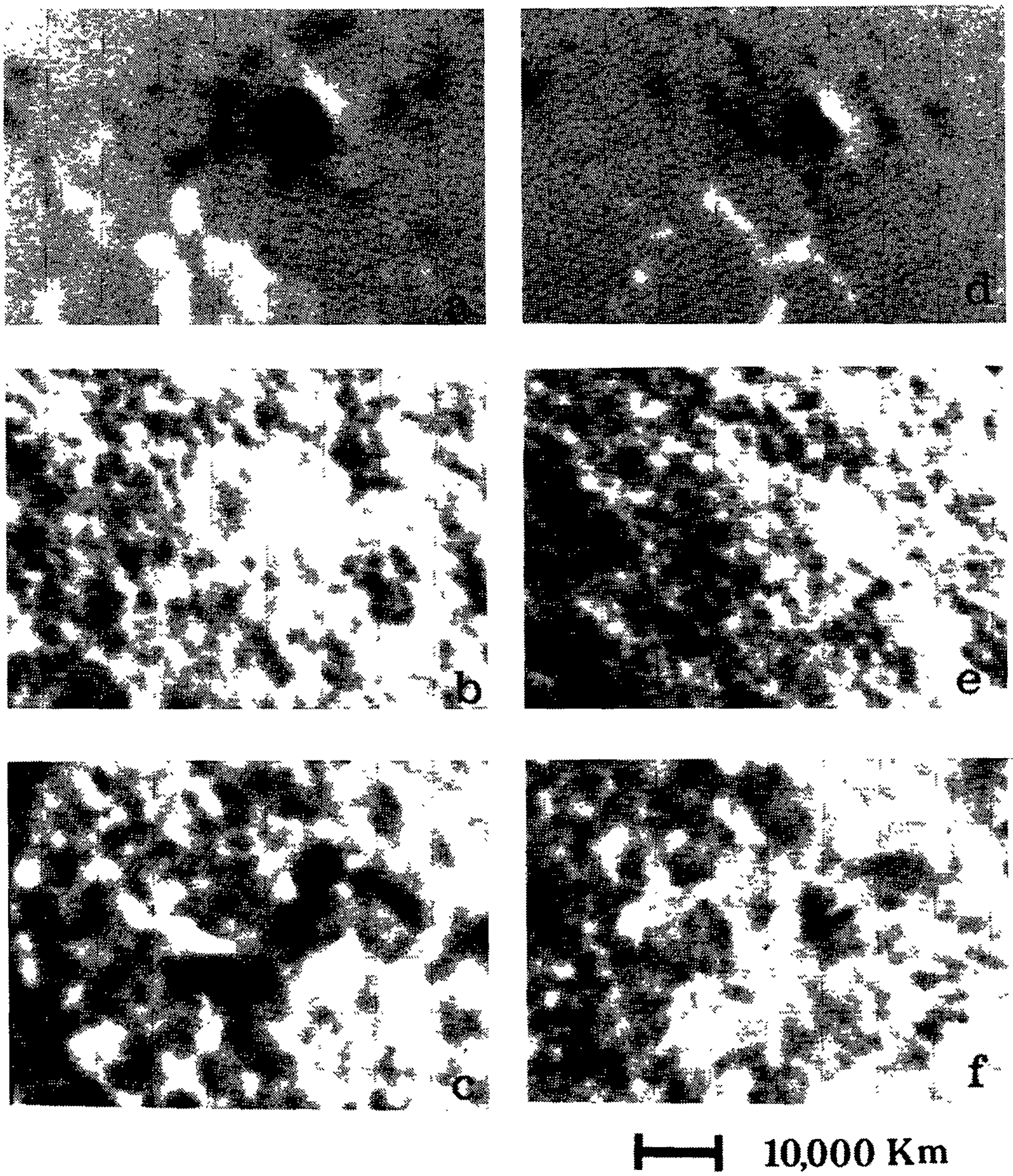

Fig. 5. (a) Longitudinal magnetogram of 26 September 1987; (b) photospheric Dopplergram of 26 September, 1987; (c) chromospheric Hβ Dopplergrams of 26 September, 1987; (d) longitudinal magnetogram of 27 September 1987; (e) photospheric Dopplergram of 27 September, 1987; (f) chromospheric Hβ Dopplergrams of 27 September, 1987; in the Dopplergrams, white velocities correspond to downward flows; black, upflows.

where the outflow appears as a red shift. By tracking individual features, we found that the speed of mixed polarity MMFs is about 1.0–2.0 km s^{-1}, which is greater than photospheric Doppler measurement. This is consistent with the model demonstrating kinks moving outward at Alfvén velocity, relative to the streaming gas (Meyer *et al.*, 1974). These mixed polarity MMFs do not carry a net flux away from the sunspot. On the other hand, some negative magnetic fluxes (with the same polarity as the center spot) move outward from the edge of the sunspot at an average speed of about 0.5 km s^{-1}, consistent with the corresponding photospheric Doppler velocity. The moving mecha-

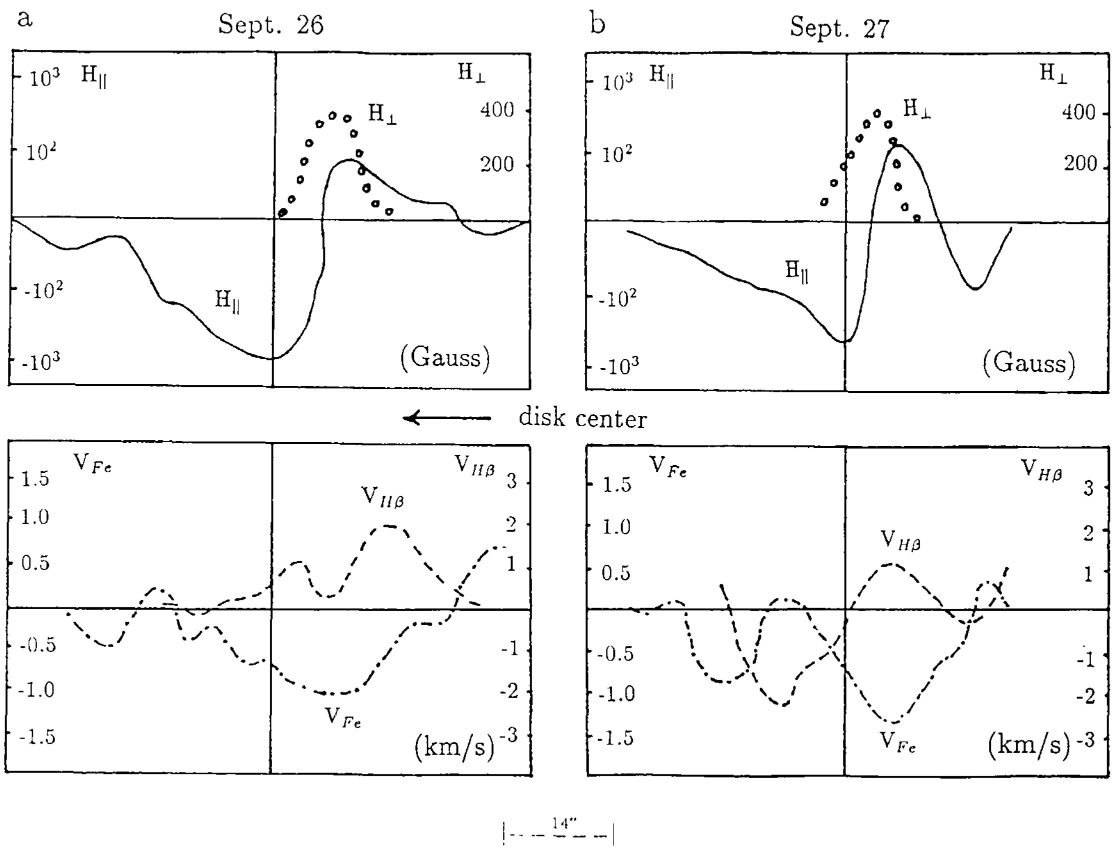

Fig. 6. The profiles of magnetic and velocity field strength through the sunspot on 26(a) and 27(b) September, 1987. Solid lines indicate longitudinal magnetic field; dotted lines indicate transverse magnetic field; dash-dot lines indicate photospheric velocity field; dashed lines indicate chromospheric velocity field.

nism of these magnetic fragments may be different from that of mixed polarity MMFs discussed above. These uni-polar MMFs probably represent the fragmentation and decay process of sunspots, and the fragments are driven by the photospheric Doppler flow.

4.2. The Chromospheric Mass Flow of Sunspot

Figure 6 also compares the measured photospheric and chromospheric Doppler velocities. The most striking features shown in Figure 6 are that the chromospheric and photospheric velocities are generally in the opposite directions; i.e., if the chromosphere has a blue shift, the photosphere has a red shift. On 26 September, the maximum of the chromospheric velocity is slightly offset from the minimum photospheric velocity. On 27 September these maximum and minimum velocities coincide. It means that the direction of the chromospheric mass motion in the penumbra and superpenumbra is inward, contrasting with the outflow in the photosphere. In the umbra, the chromospheric mass appears to flow upward (black in Figure 5). Dialetis, Mein, and Alissandrakis (1985) have studied the steady-state characteristics of the Evershed flow in the chromosphere and photosphere and compared them with the topology of the magnetic field. They pointed out that the maximum velocity occurs in regions where the magnetic fields are almost horizontal in both layers. In general, our results (Figure 6) agree with theirs. There is one exception: on 26 September, the peak of the chromospheric Evershed flow occurs about 7000 km further away from the spot than the peak of the transverse field.

5. Summary

We obtained the following results from our first coordinated magnetograph observations of Huairou Observatory and BBSO on a decaying active region:

(a) There are two kinds of MMFs: uni-polar and mixed polarity. The mixed polarity MMFs move faster than the uni-polar MMFs which seem to be fragmented from the center spot.

(b) The extra-penumbral flow (measured by Dopplergrams) has approximately the same speed as the uni-polar MMFs (measured by tracking individual features), about 0.5 to 1.0 km s^{-1}. However, the outflow speed of the mixed polarity MMFs is between 1.0 to 2.0 km s^{-1}.

(c) The chromospheric and photospheric velocity fields are approximately in the opposite direction. In the penumbra and superpenumbra, photospheric materials move outwards; chromospheric material moves inwards. In the umbra, photospheric velocity shows downward flow, chromospheric material flows upward.

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